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DESIGN AND APPLICATION OF AN UPWARD PLUG FLOW VENTILATION SYSTEM

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ABSTRACT

By using an innovative combination of existing HVAC technologies, a displacement ventilation system has been developed and implemented successfully.

The system consists of a raised flooring system with perforated metal plates covered with a porous carpet. Supply air below room temperature is supplied from a plenum beneath the floor and rises to displace the warmed room air. The return air is collected in a ceiling plenum and is treated by an electronic air cleaner and an acid-treated activated carbon filter to remove particulate and certain gas phase components. The treated air is then mixed with outside air and conditioned with conventional heating and cooling coils to adjust its temperature and humidity.

This system was developed and evaluated in a simulation room at the Philip Morris Research Center in Richmond, Virginia. A commercial application is in use as a smoking accommodation lounge in a performing arts center[2]. Measurements of numerous indoor air quality parameters have shown significant improvements in these

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parameters over conventionally ventilated rooms, as well as consistently even temperature and relative humidity levels.

INTRODUCTION

Indoor air quality (IAQ) is becoming increasingly more important in the design and operation of HVAC systems. This research addresses some of the shortcomings of conventional mixed-room ventilation with a new system using upward displacement ventilation and removal of airborne substances from return air.

ASHRAE Standard 62-1989, "Ventilation for Acceptable Indoor Air Quality", allows two options for obtaining acceptable indoor air quality: the Ventilation Rate Procedure[3] which specifies the amount of outside air per person for a variety of situations and the Indoor Air Quality Procedure[4] that allows reducing outside air makeup rates if recognized concentration standards for specific substances are met.

The objective of this research was to develop a ventilation system that can improve indoor air quality using readily available technologies meeting the Indoor Air Quality Procedure; thereby requiring less outside air and energy. The specific application reported here is for a smoking accommodation lounge.

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3 ASHRAE 62-1989, Table 2
4 ASHRAE 62-1989 Apendix C, Table C-4

DESIGN APPROACH

In assessing the performance of conventional ventilation systems[5], three issues were identified.

- A conventional system can eliminate substances generated in the room by exhausting a sufficient portion of the return air and replacing it with fresh outside air. This dilution approach can be energy intensive, depending upon the system design, due to the conditioning load for the makeup-air.
- In ceiling supply and return systems, ventilation efficiency can be reduced by supply air "short circuiting" to the ceiling return.
- Because the room is mixed, the concentration of airborne substances[6] introduced into or generated within the space decay more slowly than plug flow systems.

The design approach for the displacement system was to address these three issues by removing substances from the return air stream using readily available technologies and by using an upward, floor-to-ceiling, ventilation system. These techniques were expected to improve the overall system efficiency by:

- Reducing outside air required (by partial recirculation), and thus conserving energy .

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5 Ceiling supply and return mixed room systems
6 such as organic material, microbes, and particulate

- Sweeping airborne substances up and away from the breathing zone of the room's occupants.
- Reducing cross-contamination from other parts of the room.

This system was first evaluated in a specially constructed simulation room shown schematically in Figure 1. The room dimensions were 14 ft X 14 ft X 11 ft (4.27 m X 4.27 m X 3.35 m). Supply air from a standard air handling unit (AHU) was directed into a supply air plenum beneath a raised floor. The floor was a perforated metal plate[7] covered by commercial woven carpet[8]. The return air, collected in a ceiling plenum, was treated by an electronic air cleaner for particulate removal and an acid-treated carbon filter to remove gas phase substances.

Variable speed fans and dampers were installed for flexibility in adjusting fresh air supply and return air rates. Instrumentation was added for flow, temperature, and relative humidity measurement at various points in the system.

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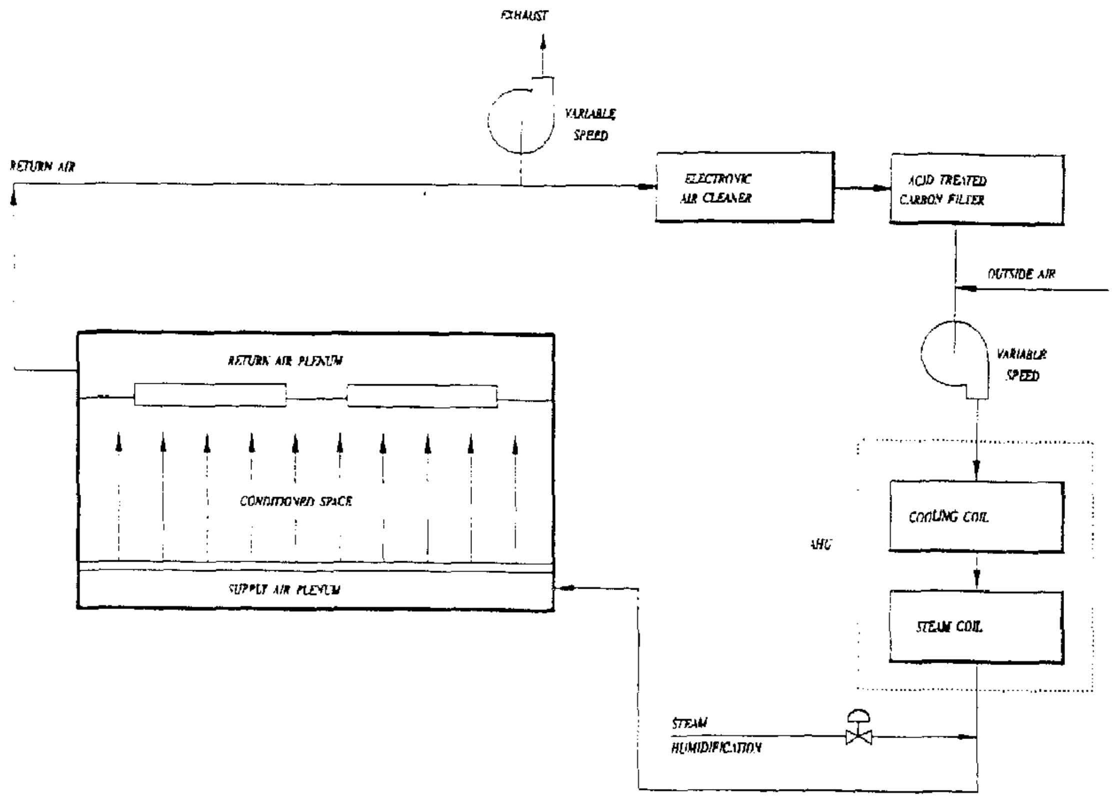
7 23% open area, 3/16 in (4.7 mm) diameter perforations.
8 Standard commercial grade woven carpet with modified backing permitting air flow.

Figure 1

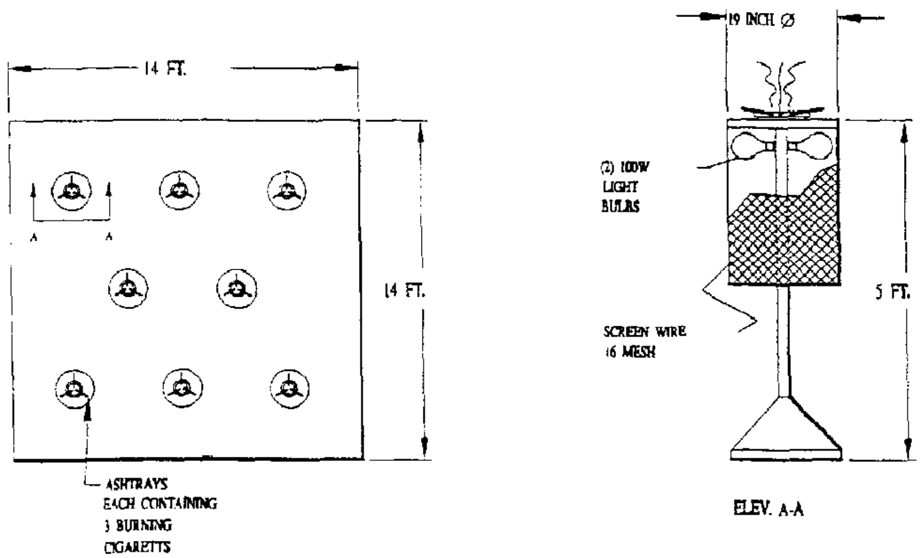

EXHAUST
VARIABLE SPEED
RETURN AIR
ELECTRONIC AIR CLEANER
ACID TREATED CARBON FILTER
OUTSIDE AIR
VARIABLE SPEED
RETURN AIR PLENUM
CONDITIONED SPACE
SUPPLY AIR PLENUM
AHU
COOLING COIL
STEAM COIL
STEAM HUMIDIFICATION

RESULTS

Simulation Room

Evaluations of the system performance in the simulation room were made using stands constructed to simulate smoking and the approximate thermal loads of the occupants in the room. Each stand was equipped with two 100-watt light bulbs and a heat dissipating assembly, as well as three continuously burning cigarettes at an elevation of 5 ft (1.52 m) above the floor. Eight stands were placed in the in the simulation room, as shown in Figure 2. This loading approximately simulates 30 people in the room with 24 of them smoking; an extremely high smoking rate.

Figure 2



The Ventilation Rate Procedure of ASHRAE 62-1989 would require 1,800 cfm (850 l/s) of outside air to ventilate the simulation room. Measurements of particulate, nicotine, and ammonia were used as tracers so that the effectiveness of displacement ventilation in a high density smoking environment could be evaluated. Based on these results, it was found that 900 cfm (430 l/s) of outside air[9], mixed with 900 cfm (430 l/s) of treated recycle air, produced acceptable air quality[10] with the upward displacement ventilation system.

The following table compares particulate, ammonia, and nicotine in the breathing zone (5.5 ft) of the simulation room to the calculated concentrations of these substances in a conventionally ventilated well-mixed room with the same artificially high smoking rate. The circulation and makeup air rates, and treatment of the return air are identical. The total particulate, airborne and tobacco, measured in the breathing zone was less than the 0.1 mg/m^3 listed in ASHRAE 62-1989 Table C-4. The ammonia and nicotine measurements were much lower than the OSHA standard for eight hours allowable exposure of 17 mg/m^3 and 0.5 mg/m^3 respectively. These concentrations were judged to comply with the Indoor Air Quality Procedure for the displacement ventilated room.

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9 Half of that required by the Ventilation Rate Procedure

10 Complies with ASHRAE 62-1989 Indoor Air Quality Procedure

Table 1

Equilibrium Concentration of:	Displacement Room (Measured)	Mixed Room (calculated[1])
Total Particulate[2], mg/m^3	<0.1	0.9
Ammonia[3], mg/m^3	0.07	0.5
Nicotine[4], mg/m^3	0.02	0.25

[1] Based upon measured cigarette generation rates for particulate, ammonia, and nicotine of 1.75 mg/min, 1.0 mg/min, and 0.5 mg/min respectively

[2] 2 minute sample collected on a piezo balance

[3] 1 hour collection on H_2SO_4/silica gel, analyzed by water extraction - ion chromotography

[4] 1 hour collection on XAD-4 resin analyzed by methylene chloride extraction - gas chromotography

At 1,800 cfm (850 l/s), the velocity through the floor was approximately 10 ft/min (0.05 m/s). Pressure drop across the carpet was measured at 0.025 in of water (6.2 Pa). Point-to-point velocities across the entire floor were very uniform (within ±10%). At this low velocity, there is no feet or ankle discomfort.

Benedum Center Lounge

The displacement ventilation system described for the simulation room was scaled-up for the Benedum lounge using a 3.3:1 scale factor. The lounge specifications were:

- 660 ft^2 (61.3 m^2) of occupied space
- 100 occupants, 80% smoking
- Recycled air -- 3000 cfm (1420 l/s), through
  - an electronic air cleaner[11], and
  - a phosphoric acid treated carbon filter[12]
- Outside air -- 3000 cfm (1420 l/s)

Following completion of the lounge, the owner contracted with an indoor air quality testing company to evaluate air quality in the lounge. Samples were taken of the outside air, air in the lobby adjacent to the lounge, and at the floor, breathing zone, and ceiling elevations at the perimeter and center of the lounge during various occupancy periods. Thirty-three smokers were representative of the smoking level that had actually been observed since the lounge opening (design maximum was 80). The results are shown in Table 2.

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11 Face velocity of 10.5 ft/s (3.2 m/s), ionization voltage of 12,000

12 4-10 mesh carbon with 10% phosphoric acid, superficial contact time of 0.15 seconds

Table 2

	Outside Air	Lobby	Lounge[1]	Lounge	Lounge	Lounge
People Present			2	28	33	3
Smoking	No	No	No	No	Yes	No
Temperature, °F/°C	71.4/21.9	71.2/21.8	67.8/19.9	71.5/21.9	72.6/22.6	71.0/21.7
Relative Humidity, %	39.3	42	48.5	45.1	42.4	42.8
Particulate, mg/m^3	0.05	0.03	0.02	0.01	0.03	0.02
Nicotine, mg/m^3		<0.001	<0.001	<0.001	0.01	<0.001
Carbon Monoxide, ppm	2	2	2	2	3	2
Carbon Dioxide, ppm	350	350	350	400	500	400
Microbial Count, cfu/m^3	701	588	163	412	449	96

1 Measurements reported here were taken at the breathing zone elevation in the center of the roor

These resul[illegible] [illegible]en adjusted for the number of people, agree very well with the results obtained with displacement ventilation in the simulation room.

Twenty-seven volatile organic compounds [13](VOC's) were also screened[14]. Table 3 shows the concentrations that were above detectable limits.

13 Benzene, 2-Butanone, Carbon Disulfide, Carbon Tetrachloride, Chlorobenzene, Chloroethane, Chloroform, Chloromethane, 1,4 Dichlorobenzene, 1,1 Dichloroethane, Ethylbenzene, Isopropyl Ether, 4-Methyl-2-Pentanone, Methyl-t-Butyl Ether, Methylene Chloride, Naphtalene, Styrene, 1,1,2,2-Tetrachloroethane, Tetrachloroethane, Toluene, 1,1,2 -Trichloroethane, 1,1,1 -Trichloroethane, Trichloroethane, Trichlorofluoromethane, Vinyl Chloride, Xylene (total)

Table 3

Compound, $\mu g/m^3$	Outside Air No smoking	Lobby No smoking	Lounge 33 occupants, smoking
Benzene,	<1.3	4.5	<1.3
2-Butanone	<2.6	3.6	<2.6
Ethylbenzene	<1.3	3.8	<1.3
Methylene Chloride	<1.3	1.9	1.8
Tetrachloroethane	<1.3	7.7	<1.3
Toluene	13	12	<1.3
1,1,1-Trichloroethane	2.8	14	1.6
Trichloroflurομethane	2.6	2.4	3.1
Xylene (total)	1.8	16	<1.3

Normal housekeeping and HVAC maintenance have been sufficient to maintain the lounge.

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14 EPA Method TO-1

CONTINUING STUDIES

Additional research and equipment evaluations are in progress, or planned, which will address other aspects of upward (and through-the-carpet) displacement ventilation, including:

- Relative life-cycle cost (installed cost plus operating cost).
- Velocity gradients (mixing) caused by cold walls and other factors.
- Velocity required to maintain plug flow and good vertical separation between the "clean" and "dirty" portions of the room.
- Control systems.
- Carpet maintenance.
- Entrainment of particulate from the carpet into the space.

CONCLUSIONS

Well designed and maintained conventional mixed room ventilation systems that comply with ASHRAE 62-1989 can provide acceptable indoor air quality. The

displacement ventilation process described in this paper can further reduce the breathing zone concentrations of a wide variety of substances and provide the opportunity for energy conservation by permitting recirculation a portion of the exhaust air after treatment to remove particulate and gas phase substances.

While this application is a special case, that is high density smoking, the principles described here may be used in a wide variety of indoor environments.

ACKNOWLEDGEMENTS

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